

WO03050577

Publication Title:

Single mode dispersion compensating optical fiber

Abstract:

A single mode dispersion and dispersion slope compensating optical fiber includes a central core segment, a depressed moat segment, an annular ring segment, and a cladding layer. Each of the segments of the fiber have a relative refractive index that are selected to provide negative dispersion at a wavelength of within the range of about 1530 nm to about 1620 nm, negative dispersion slope at a wavelength of within the range of about 1530 nm to about 1620 nm, a kappa value of within the range of 40 to about 60 at a wavelength of about 1550 nm, and a fiber cut-off wavelength of less than about 1650 nm, and more preferably less than 1550 nm

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(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
19 June 2003 (19.06.2003)

PCT

(10) International Publication Number
WO 03/050577 A1

(51) International Patent Classification⁷: **G02B 6/16**,
6/22, H04B 10/18

(21) International Application Number: PCT/US02/35859

(22) International Filing Date:
8 November 2002 (08.11.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10/014,781 11 December 2001 (11.12.2001) US

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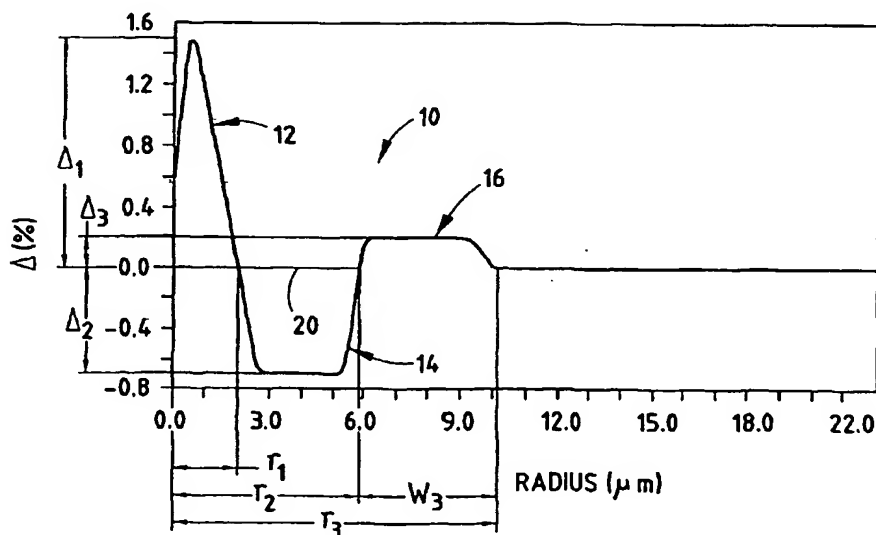
(81) Designated States (*national*): AE, AG, AL, AM, AT, AU,
AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,
CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH,
GM, HR, HU, ID, IL, IN, IS, JP, KB, KG, KP, KR, KZ, LC,
LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW,
MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG,
SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC,
VN, YU, ZA, ZM, ZW.

(84) Designated States (*regional*): European patent (AT, BE,
BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT,
LU, MC, NL, PT, SE, SK, TR).

Published:
— with international search report

[Continued on next page]

(54) Title: SINGLE MODE DISPERSION COMPENSATING OPTICAL FIBER



(57) Abstract: A single mode dispersion and dispersion slope compensating optical fiber (10) includes a central core segment (12), a depressed moat segment (14), an annular ring segment (16), and a cladding layer (18). Each of the segments of the fiber have a relative refractive index that are selected to provide negative dispersion at a wavelength of within the range of about 1530 nm to about 1620 nm, negative dispersion slope at a wavelength of within the range of about 1530 nm to about 1620 nm, a kappa which is defined as the ratio of the dispersion to the dispersion slope value of within the range of 40 to about 60 at a wavelength of about 1550 nm, and a fiber cut-off wavelength of less than about 1650 nm, and more preferably less than 1550 nm.

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— before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments

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SINGLE MODE DISPERSION COMPENSATING OPTICAL FIBER

[0001] This application claims the benefit of and priority to U.S. Patent Application Number 10/014,781, filed 12/11/01.

BACKGROUND OF THE INVENTION

[0002] Field of the Invention

The present invention relates to dispersion compensating (DC) optical fibers, and more particularly to single mode DC fibers that are particularly well suited for compensating for dispersion in transmission fibers having κ values of less than 100.

[0003] Technical Background

To meet the ongoing drive for more bandwidth at lower costs, telecommunications system designers are turning to high channel count dense wavelength division multiplexing architectures, longer reach systems and higher transmission bit rates. This evolution makes chromatic dispersion management critical to systems performance as system designers now desire the ability to accurately compensate dispersion across entire channel plans. More specifically, the increased demand for higher bit transmission rates has resulted in a large demand for optical transmission systems that can control dispersion effects. An analysis of common optical transmission systems indicates that while such systems can tolerate about 1,000 ps/nm residual dispersion at 10 Gbit/second, these systems tolerate only about 62 ps/nm residual dispersion at a higher transmission rate of 40 Gbit/second. Therefore, it is important to accurately control the dispersion for such high bit rate transmissions. This control becomes increasingly important as the transmission rate increases. Further, the need to accurately control dispersion means that dispersion slope of a transmission fiber must also be compensated for, particularly as transmission rates approach 40 Gbit/second.

[0004] Various solutions have been proposed to achieve the low dispersion and dispersion slope values required for compensating non-zero dispersion shifted fibers (NZDSFs), including: photonic crystal fibers, higher order mode dispersion compensation fibers, dispersion compensating gratings and dual fiber dispersion compensating techniques. Each of these solutions have drawbacks associated therewith.

[0005] Photonic crystal fibers are designed to have a large negative dispersion and a negative dispersion slope that are close to those required for compensating NZDSFs. However, photonic crystal fibers have drawbacks including a relatively small effective area of about $10 \mu\text{m}^2$ or less that leads to unacceptably high splice losses and hence requires the use of a specially designed transition or bridge fiber to reduce splice losses. In addition, due to the very nature of photonic crystal fibers, i.e., glass/air interfaces in the core of the fiber, the related attenuation is unacceptable in the transmission window of interest. Further, photonic crystal fibers are significantly difficult to manufacture on a large scale and are, therefore, expensive.

[0006] Higher order mode (HOM) dispersion compensation relies on the dispersion properties of a HOM fiber propagating higher order modes. It has been demonstrated that higher order modes, e.g. LP_{02} and LP_{11} , have higher negative dispersions and dispersion slopes than fundamental modes. HOM dispersion compensation typically relies on the conversion of a transmitted fundamental mode to one of the higher order modes via a mode converter. Subsequently, this higher order mode is propagated in the HOM fiber that supports that mode. After a finite distance, the higher order mode is converted back to the fundamental mode via a second mode converting device. Problems associated with HOM dispersion compensation solutions include inefficient mode converters and difficulty of producing HOM fibers that allow higher order mode transmission while resisting coupling to the fundamental mode.

[0007] Dispersion compensating gratings are utilized to achieve a required differential group delay via chirped gratings. Techniques utilizing dispersion compensating gratings have been shown to be useful only for narrow bands, as these techniques typically suffer from dispersion and dispersion slope ripple when the required grating length becomes large.

[0008] In dual fiber dispersion compensating fiber solutions for NZDSFs, the dispersion and slope compensation are partially de-coupled and separately treated in each fiber. Typically, dual fiber dispersion compensating techniques include the use of a dispersion compensating fiber followed by a dispersion slope compensating fiber. Such solutions require the use of a dispersion slope compensating fiber that compensates for a relative small dispersion slope. Further, such solutions are subject to additional splice losses and are a comparatively complex solution.

[0009] Extensive profile modeling of optical fibers has resulted in well-established correlations between dispersion slope, effective area and bend sensitivity. By increasing the role played by wavelength dispersion in a given fiber, it is possible to decrease the slope and even create a negative slope in some cases. However, as the effective area is decreased, the bend sensitivity of the fiber is increased. The effective area of the fiber can be further increased, but generally at the expense of further degradation of the bend sensitivity. Decreasing the dispersion slope, or making the dispersion slope negative, results in working close to the cut-off wavelength of the fundamental mode, which in turn makes the fiber more bend sensitive and results in greater signal loss at wavelengths greater than 1560 nm. As a result of these relationships, it is extremely difficult to manufacture a viable DC fiber that compensates both dispersion and dispersion slope effectively. Moreover, when κ (dispersion/dispersion slope) is low, it is difficult to adequately compensate for dispersion over wide wavelength bands.

[00010] Heretofore, the most viable broad band commercial technology available to reduce or eliminate dispersion has been DC fiber modules. As dense wavelength division multiplexing deployments increase to 16, 32, 40 and more channels, broad band DC products are desired. Further, as interest increases in higher bit-rate information transmission, i.e., greater than 40 Gbit/second, ultra-long reach systems, i.e., systems greater than 100 km in length, and optical networking, it has been imperative to use DC fibers even on networks that carry data on NZDSFs. One such NZDSF is LEAF® optical fiber, manufactured by and available from Corning Incorporated of Corning, New York. LEAF® fiber is a positive NZDSF that has been the optical fiber of choice for many new systems due to its inherently low dispersion and economic advantage over conventional signal mode fibers.

[00011] The combination of the early versions of DC fibers with NZDSFs effectively compensated dispersion at only one wavelength with significant residual system dispersion being present within the operating band at wavelengths away from that one wavelength. However, higher bit-rates, longer reaches and wider bandwidths require dispersion slope to be compensated for more exactly. Consequently, it is desirable for the DC fiber to have dispersion characteristics such that its dispersion and dispersion slope are matched to that of the transmission fiber it is required to compensate.

[00012] Therefore, it would be desirable to develop alternative DC fibers, particularly fibers having the ability to compensate for dispersion and dispersion slope of NZDSFs and other positive dispersion optical fibers over a wide wavelength band of around 1550 nm.

BRIEF DESCRIPTION OF THE DRAWINGS

- [00013] Fig. 1 is a schematic cross-sectional view of a novel optical waveguide embodying the present invention;
- [00014] Fig. 2 is a diagram of a waveguide refractive index profile of the present inventive dispersion compensating fiber;
- [00015] Fig. 3 is a diagram of a waveguide refractive index profile of first embodiment of the dispersion compensating optical fiber;
- [00016] Fig. 4 is a diagram of a waveguide refractive index profile of a second embodiment of the dispersion compensating optical fiber;
- [00017] Fig. 5 is a diagram of a waveguide refractive index profile of a third embodiment of the dispersion compensating optical fiber;
- [00018] Fig. 6 is a diagram of a waveguide refractive index profile of a fourth embodiment of the dispersion compensating optical fiber;
- [00019] Fig. 7 is a graph diagram of dispersion versus wavelength for LEAFTM fiber, a dispersion compensating fiber and the total dispersion for the combination thereof; and
- [00020] Fig. 8 is a schematic view of a fiber optic communication system employing the optical waveguide fiber of the present invention.

SUMMARY OF THE INVENTION

[00021] The present invention meets the need for a DC fiber that compensates for dispersion and dispersion slope of a NZDSF. The DC fiber disclosed herein enables accurate and substantially complete compensating for dispersion and dispersion slope for a NZDSF wherein such DC fiber exhibits both negative total dispersion and negative dispersion slope at 1550 nm.

[00022] One embodiment of the present invention is a dispersion and dispersion slope compensating optical fiber that includes a central core segment having a relative refractive index, a depressed moat segment on the periphery of the central core segment and having a relative refractive index that is less than the relative refractive index of the central core segment, an annular ring segment on the periphery of the depressed moat segment and having relative refractive index that is less than the relative refractive index of the central core segment and greater than the relative refractive index of the depressed moat segment, and a cladding layer on the periphery of the depressed moat segment and having a relative refractive index that is less than the relative refractive index of the annular ring segment and greater than the relative refractive index of the depressed moat segment. The relative refractive indices of the segments are selected to provide negative dispersion at a wavelength of within the range of from about 1530 nm to about 1620 nm, negative dispersion slope at a wavelength of within the range of from about 1530 nm to about 1620 nm, a $kappa$ value of within the range of from about 40 to about 60 at a wavelength of about 1550 nm, and a fiber cut-off wavelength of less than about 1650 nm.

[00023] Another embodiment of the present invention relates to a dispersion and dispersion slope compensating optical fiber that includes a central segment having a relative refractive index, a first annular segment surrounding the central segment and having a relative refractive index that is less than the relative refractive index of the central segment, a second annular segment surrounding the first annular segment and having a relative refractive index that is less than the relative refractive index of the central segment and greater than the relative refractive index of the first annular segment, and a cladding layer surrounding the second annular segment and having a relative refractive index that is less than the relative refractive index of the second annular segment and greater than the relative refractive index of the first annular segment. The relative refractive indices are selected to provide negative

dispersion at a wavelength of within the range of from about 1530 nm to about 1620 nm, negative dispersion slope at a wavelength of within the range of from about 1530 nm to about 1620 nm, a κ value of less than or equal to about 100 at a wavelength of about 1550 nm, and a fiber cut-off wavelength of less than about 1550 nm.

[00024] The present invention also includes optical communication systems employing dispersion and dispersion slope compensating fibers in accordance with the embodiments described above.

[00025] The present invention utilizes single waveguide optical fibers to accurately and completely compensate for both dispersion and dispersion slope, thereby eliminating the need for high cost compensating materials and components and/or the required use of compensating fibers that are difficult and expensive to manufacture and which contribute to significant signal loss.

[00026] Additional features and advantages of the present invention will be set forth in the detailed description which follows and will be apparent to those skilled in the art from the description or recognized by practicing the invention as described in the description which follows, together with the claims and appended drawings.

[00027] It is to be understood that the foregoing description is exemplary of the invention only and is intended to provide an overview for understanding the nature and character of the invention as it is defined in the claims. The accompanying drawings are included to provide a further understanding of the invention and are incorporated and constitute part of this specification. The drawings illustrate various features and embodiments of the invention, which, together with their description serve to explain the principals and operation of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[00028] For purposes of the description herein, it is to be understood that the invention may assume various alternative orientations and step sequences, except where expressly specified to the contrary. It is also to be understood that the specified devices and processes illustrated in the attached drawings, and described in the following specifications are exemplary embodiments of the inventive concepts defined in the appended claims. Hence, specific dimensions and other physical characteristics relating to the embodiments disclosed herein are not to be considered as limiting unless the claims expressly state otherwise.

Definitions

[00029] The following definitions and terminology are commonly used in the art.

[00030] -The radii of the segments of the core are defined in terms of the index of refraction of the material of which the segment is made. A particular segment has a first and a last refractive index point. A central segment has an inner radius of zero because the first point of the segment is on the center line. The outer radius of the central segment is the radius drawn from the waveguide center line to the last point of the refractive index of the central segment. For a segment having a first point away from the center line, the radius from the waveguide center line to the location of its first refractive index point is the inner radius of that segment. Likewise, the radius from the waveguide center line to the location of the last refractive index point of the segment is the outer radius of that segment. The radii of the segments may be conveniently defined in a number of ways. In this application, radii are defined in accordance with the figures, described below.

[00031] -The relative index of a segment, $\Delta\%$, as used herein, is defined by the equation,

$$\Delta\% = 100 \times \frac{n_i^2 - n_c^2}{2n_c^2},$$

where n_i is the maximum refractive index of the index profile segment denoted as i , and n_c , the reference refractive index, is taken to be the minimum index of the clad layer. Every

point in the segment has an associated relative index. The maximum relative index is used to conveniently characterize a segment whose general shape is known.

[00032] -The term refractive index profile or index profile is the relation between $\Delta\%$ or refractive index and radius over a selected segment of the core.

[00033] -The bend loss of a waveguide fiber is expressed as induced attenuation under prescribed test conditions. The bend test referenced herein is used to compare relative resistance of waveguide fiber to bending. To perform the test, a DC fiber according to the invention with a length of longer than 1 km is wound about a mandrel of 6 inches in diameter without any tension. Then the attenuation of the DC fiber is measured using a standard Optical Time Domain Reflectometry (OTDR) instrument at the wavelength of 1550 nm.

[00034] -The effective area is generally defined as,

$$A_{\text{eff}} = 2\pi(\int E^2 r dr)^2 / (\int E^4 r dr),$$

wherein the integration limits are zero to ∞ , and E is the electric field associated with the propagated light.

[00035] -The relationship between a transmission fiber and a dispersion compensating fiber that completely compensates for the dispersion of the transmission fiber follows the general equation of:

$$D_{DC}(\lambda)L_{DC} = -D_T(\lambda)L_T,$$

wherein $D_{DC}(\lambda)$ is the dispersion of the dispersion compensating fiber, L_{DC} is the length of the dispersion compensating fiber, $D_T(\lambda)$ is the dispersion of the transmission fiber, λ is a wavelength in the optical transmission band, and L_T is the length of the transmission fiber.

- The desired relationship of the κ of the optical fibers in transmission line is as follows:

$$\kappa_{DC}(\lambda) = \frac{D_{DC}}{S_{DC}} = \kappa_T(\lambda) = \frac{D_T}{S_T},$$

wherein $\kappa_{DC}(\lambda)$ is the κ value for the dispersion compensating fiber at a particular wavelength, D_{DC} is the dispersion for the dispersion compensating fiber, S_{DC} is the dispersion slope for the dispersion compensating fiber, $\kappa_T(\lambda)$ is the κ value for the transmission fiber at the same wavelength, D_T is the dispersion for the transmission fiber, and S_T is the dispersion slope for the transmission fiber.

[00036] The dispersion and dispersion slope compensating optical fiber described and disclosed herein has a generally segmented core. Each of the segments is described by a refractive index profile, relative refractive index percent, $\Delta_i\%$, and an outside radius, r_i . The subscript of i on Δ and r refers to a particular segment. The segments are numbered 1-n beginning with the inner most segment which includes the waveguide long axis centerline. The clad layer having a refractive index, n_c , surrounds the core.

[00037] The radius, relative refractive index percent, and refractive index profile of each segment of the DC fiber are selected to provide: negative dispersion at a wavelength of within the range of from about 1530 nm to about 1620 nm; negative dispersion slope at a wavelength of within the range of from about 1530 nm to about 1620 nm; a κ value of within the range of from about 40 to about 60 at a wavelength of about 1550 nm; and, a fiber cut-off wavelength of less than about 1650 nm.

[00038] The DC fiber according to the invention described and disclosed herein has a generally segmented structure, as shown in Fig. 1. Each of the segments is described by a refractive index profile, relative refractive index percent, Δ_i , and an outside radius, r_i . The subscript i for the r and Δ refers to a particular segment. The segments are numbered r_1 through r_c beginning with the innermost segment which includes the waveguide longitudinal axis center line. A clad layer having a refractive index of n_c surrounds the optical waveguide fiber. In the illustrated example, the optical waveguide compensating fiber 10 includes a central core segment 12 having an outer radius r_1 , a depressed moat segment 14 having an

outer radius r_2 , an annular ring segment 16 having an outer radius r_3 , and a width w_3 , and a cladding layer 18 having an outer radius r_c .

[00039] A general representation of the relative refractive index profile of compensation fiber 10 is illustrated in Fig. 2, which shows relative refractive index percent charted versus the compensation fiber radius. Although Fig. 2 shows only three discrete segments, it is understood that the functional requirements may be met by forming an optical waveguide compensation fiber having more than three segments. However, embodiments having fewer segments are usually easier to manufacture and are therefore preferred. Further, the fiber 10 may be constructed via a variety of methods including, but in no way limited to, vapor axial deposition (VAD), modified chemical vapor deposition (MCVD) and outside vapor deposition (OVD).

[00040] Preferably, segments 12 and 16 are formed using germanium doped SiO_2 , although other forms of index of refraction increasing dopant may also be employed to achieve the fibers disclosed herein, so long as the same general refractive index profile is achieved. Likewise, segment 14 is preferably formed using fluorine doped SiO_2 , however, other index of refraction decreasing dopants may be employed besides fluorine. Cladding layer 18 is preferably formed of pure silica, however, may also include index of refraction increasing or decreasing dopants, so long as the relationship between Δ_1 , Δ_2 , Δ_3 and Δ_c within the refractive index profile illustrated in Fig. 2 is maintained. Further, segments within profile 10 displaying a positive relative refractive index may include fluorine as a co-dopant therein, thereby reducing the final water content in the associated fiber segment and decreasing the water content therein.

[00041] The core segment 12 has a relative refractive index Δ_1 , within the range of from about 1.45% to about 2.35%, more preferably of from about 1.50% to about 1.80%, and most preferably of from about 1.50% to about 1.60%. Core segment 12 further has an outer radius r_1 , within the range of from about 2.2 μm to about 2.8 μm , more preferably within range from about 2.5 μm to about 2.7 μm , and most preferably within the range of from about 2.61 μm to about 2.64 μm . The outer radius r_1 of core segment 12 is also the inner radius of segment 14. The outer radius r_1 of core segment 12, therefore, is the intersection

of core segment 12 and moat segment 14. In this case, the intersection point is defined as the intersection of the descending portion of the index profile of core segment 12 with the horizontal axis 20, defined as the axis through an un-doped cladding layer 18 formed of SiO_2 , i.e., a $\Delta = 0\%$ relative refractive index.

[00042] The moat segment 14 has a relative refractive index 32, Δ_2 , that is less than or equal to about -0.65%, more preferably within the range of from about -1.20% to about -0.70%, and most preferably within the range of from about -0.80% to about -0.70%. Moat segment 14 has an outer radius 42, r_2 , within the range of from about 3.5 μm to about 6.0 μm , more preferably within the range of from about 4.8 μm to about 5.9 μm , and most preferably within the range of from about 5.5 μm to about 5.9 μm . The outer radius 42, r_2 , of moat segment 14 is also the inner radius of ring segment 16. The outer radius, r_2 , of moat segment 14, therefore, is the intersection of moat segment 14 and ring segment 16. In this case, the intersection point is defined as the intersection of the ascending portion of the index profile of moat segment 14 with the horizontal axis 20 as defined above. In the illustrated example, fiber 10 has a ratio of the outer diameter 42, r_1 , of core segment 12 to the outer diameter 44, r_2 , of moat segment 14 of within the range of from about 0.30 to about 0.56, more preferably within the range of from about 0.44 to about 0.55 and most preferably within the range of from about 0.44 to about 0.48.

[00043] The ring segment 16 has a relative refractive index 34, Δ_3 , within the range of from about 0.10% to about 0.30%, more preferably within the range from about 0.18% to about 0.20%, and most preferably within the range from about 0.19% to about 0.20%. Ring segment 16 has a central radius 44, r_3 , within the range of from about 6.0 μm to about 8.5 μm , more preferably within the range of from about 6.5 μm to about 7.7 μm , and most preferably within the range of from about 7.3 μm to about 7.4 μm . For profiles having more than one annular segment, such as the example illustrated in Fig. 2, the outer most annular segment, such as ring segment 16, is characterized by a width. Ring segment 16 has a width 46 of about 4.0 μm . In the illustrated example, width 46 is defined by the distance between the intersection of the ascending portion of the profile of moat segment 14 with the horizontal axis 20 as defined above, and the intersection of the descending portion of the profile of ring segment 16 with the horizontal axis 20 as defined above. It should be noted that the relative

refractive index, Δ_3 , and radius, r_3 , of ring segment 16 can vary more than in core segment 12 and moat segment 14. For example, a higher and narrower ring segment 16 may be replaced by a shorter and wider ring segment 16 to achieve a fiber exhibiting the desired properties in accordance with the invention.

[00044] The radii, relative refractive indices and refractive index profile of each segment of the overall profile of fiber 10 are selected to provide the following optical properties at a wavelength of about 1550 nm: a negative total dispersion, more preferably a dispersion of between -140 ps/nm-km to about -240 ps/nm-km, and most preferably within the range of from about -200 ps/nm-km to about -240 ps/nm-km; a negative dispersion slope, and more preferably a dispersion slope of less than or equal to about -2.5 ps/nm², a κ value of less than or equal to about 100, more preferably less than or equal to about 60, and most preferably within the range of from about 40 to about 60; a fiber cut-off wavelength of less than 1650 nm, more preferably less than 1550 nm, even more preferably within the range of from about 1470 nm to about 1530 nm, even more preferably of less than or equal to about 1500 nm, and most preferably of less than or equal to 1450 nm; and, an effective area of greater than or equal to about 8 μm^2 , more preferably greater than or equal to about 15 μm^2 , and most preferably greater than or equal to about 18 μm^2 .

EXAMPLES

[00045] The invention will be further illustrated by the following examples which are meant to be illustrative and exemplary of the invention.

[00046] In example 1, as listed in Table 1, and illustrated in Fig. 3, a fiber having a refractive index profile includes a core region 12 having a peak relative refractive index, Δ_1 , of 1.51% and an outer radius, r_1 , of 2.62 μm , a moat segment 14 having a relative refractive index, Δ_2 , of about -0.70% and an outer radius, r_2 , of about 5.90 μm , and a ring segment 16 having a relative refractive index, Δ_3 , of about 0.19% and a width w_3 of about 4.0 μm . The raised index segments 12 and 16 were formed using germanium doping while the lowered index segment 14 was formed using fluorine doping. Cladding segment 18 includes undoped silica, and has an outer radius of about 6.25 μm . The fiber of example 1 exhibits a dispersion of -148 ps/nm-km at a wavelength of about 1550 nm, a dispersion slope of 3.02 ps/nm²-km at 1550 nm at a wavelength of about 1550 nm, and a κ value of about 49 also at a

wavelength of about 1550 nm. The fiber of example 1 further exhibits a cut-off wavelength of about 1637 nm, a zero dispersion wavelength of about 1501 nm, and an effective area of about $18.6 \mu\text{m}^2$ at a wavelength of about 1550 nm.

[00047] Additional examples of dispersion and dispersion slope compensating fibers in accordance with the invention are listed in Table 1, and corresponding Figs. 3-6.

TABLE 1

	Ex. 1	Ex. 2	Ex. 3	Ex. 4
Corresponding Figure	3	4	5	6
Δ_1 (%)	1.92	2.00	2.32	2.32
r_1 (μm)	2.62	2.63	2.63	1.29
Δ_2 (%)	-0.70	-0.80	-1.20	-1.20
r_2 (μm)	5.90	5.50	4.80	3.80
Δ_3 (%)	0.19	0.20	0.18	0.18
r_3 (%)	7.70	7.34	6.50	6.50
Ring width (μm)	4.00	4.00	4.00	4.00
Dispersion (ps/nm-km) at 1550 nm	-148	-191	-194	-174
Dispersion slope (ps/nm ² -km) at 1550 nm	-3.02	-3.82	-3.88	-3.63
κ at 1550 nm	49	50	50	48
Fiber cut-off wavelength (nm)	1637	1648	1606	1618
Zero-dispersion wavelength (nm)	1501	1500	1500	1502
Effective area (μm^2) at 1550 nm	18.6	18.64	15.00	9.63
Bend loss (dB/km) at 1550 nm	0.011	0.013	0.006	0.0003

[00048] Each of the fibers listed in the examples herein were constructed from a preform made using a plasma chemical vapor deposition lathe by depositing first a fluorine doped cladding into a SiO_2 substrate tube with a low-pressure plasma of approximately 10 Torr.

Deposition was achieved by traversing the microwave head applicator along the tube at a speed of approximately 15 cm/s while the reacting gasses, i.e., SiCl_4 , O_2 and C_2F_6 , were introduced inside the tube. A GeO_2 core was then deposited and the resulted cane was collapsed by a H_2/O_2 burner to form a solid cane. A main advantage of the plasma chemical vapor deposition method is depositing consolidated layers of glass with little or no migration of the mobile species, i.e., germanium and fluorine.

[00049] Fig. 7 illustrates the residual dispersion of a 100 km span of LEAF® fiber, manufactured by and available from Corning Incorporated of Corning, New York, coupled to approximately 4 km of dispersion compensating fiber representative of the fibers listed in Table 1. Specifically, the graph of dispersion versus wavelength in Fig. 7 includes a graphing of the dispersion of 100 km of LEAF® 100, 4 km of the percent inventive dispersion compensating fiber 102 and the total dispersion for the combination 104, the graph indicates a dispersion within the range of from about 40 ps/nm-km to about 60 ps/nm-km over a wavelength range of from about 1530 nm to about 1600 nm. Further, the graph of Fig. 7 indicates a dispersion compensation over both the C-band and L-band wavelength ranges with a single compensating fiber.

[00050] A dispersion and dispersion slope compensating optical waveguide fiber 10 manufactured in accordance with the present invention may be used in an optical fiber communication system 52, as shown in Fig. 8. System 52 includes an optical transmitter 54 adapted to transmit an optical signal in a direction indicated by an arrow 56 through an optical waveguide transmission fiber or compensated fiber 58 which is in optical communication with transmitter 54. System 52 also includes the dispersion and dispersion slope compensating fiber 10 in optical communication with transmission fiber 58 and an optical receiver 60 adapted to receive the optical signal 56. Fiber 10 may be employed within system 52 in a coil form, within a box, or in any other form or packaging as known in the art. In most systems, both ends of transmission fiber 58 and compensating fiber 10 will be capable of two-way signal transmission, and transmitter 54 and receiver 60 are shown for illustration only.

[00051] It will be become apparent to those skilled in the art that various modifications to the preferred embodiment of the invention as described herein can be made without departing

from the spirit or scope of the invention as defined by the appended claims. Thus, it is intended that the present invention covers the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

Claims

What is claimed is:

1. A dispersion and dispersion slope compensating optical fiber, comprising:
 - a central core segment having a relative refractive index;
 - a depressed moat segment on the periphery of the central core segment and having a relative refractive index that is less than the relative refractive index of the central core segment;
 - an annular ring segment on the periphery of the depressed moat segment and having a relative refractive index that is less than the relative refractive index of the central core segment and greater than the relative refractive index of the depressed moat segment;
 - and a cladding layer on the periphery of the annular ring segment and having a relative refractive index that is less than the relative refractive index of the annular ring segment and greater than the relative refractive index of the depressed moat segment;
 - and wherein the relative refractive indices are selected to provide:
 - negative dispersion at a wavelength of within the range of from about 1530 nm to about 1620 nm;
 - negative dispersion slope at a wavelength of within the range of from about 1530 nm to about 1620 nm;
 - a $kappa$ value of within the range of about 40 to about 60 at a wavelength of about 1550 nm; and
 - a fiber cut-off wavelength of less than about 1650 nm.
2. The optical fiber of claim 1, wherein the relative refractive indices are further selected to provide a dispersion slope of less than or equal to about $-2.5 \text{ ps/nm}^2\text{-km}$ at a wavelength of within the range of from about 1525 nm to about 1565 nm.
3. The optical fiber of claim 1, wherein the relative refractive indices are further selected to provide a dispersion less than or equal to within the range of about -240 ps/nm-km to about -140 ps/nm-km at a wavelength of about 1550 nm.

4. The optical fiber of claim 1, wherein the relative refractive indices are further selected to provide a fiber cut-off wavelength of within the range of from about 1470 nm to about 1530 nm.
5. The optical fiber of claim 1, wherein the relative refractive indices are further selected to provide a fiber cut-off wavelength of less than about 1450 nm.
6. The optical fiber of claim 1, wherein the relative refractive index of the central core segment is within the range of from about 1.40% to about 2.40%.
7. The optical fiber of claim 6, wherein the relative refractive index of the depressed moat segment is less than about -0.65%.
8. The optical fiber of claim 7, wherein the relative refractive index of the depressed moat segment is within the range of from about -1.20% to about -0.70%.
9. The optical fiber of claim 1, wherein the central core segment has an outer radius of within the range of about 2.2 μm to about 2.8 μm .
10. The optical fiber of claim 9, wherein the depressed moat segment has an outer radius of within the range of from about 3.5 μm to about 6.0 μm .
11. The optical fiber of claim 1, wherein the ratio of an outer radius of the central core segment to an outer radius of the depressed moat segment is within the range of from about 0.44 to about 0.55.

12. The optical fiber of claim 1, wherein the central core segment has an outer radius within the range of from about 2.2 μm to about 2.8 μm , and the relative refractive index of the central core segment is within the range of from about 1.4% to about 2.4%, wherein the depressed moat segment has an outer radius within the range of about 3.5 μm to about 6.0 μm , and the relative refractive index of the depressed moat segment is less than or equal to about -0.65%, and wherein the annular ring segment has a central radius within the range of from about 6.0 μm to about 8.5 μm and a width of about 4.0 μm , and a relative refractive index is within the range of from about 0.1% to about 0.3%.
13. The optical fiber of claim 1, wherein the relative refractive indices are further selected to provide a *kappa* value of less than or equal to about 60.

14. An optical fiber communication system, comprising:
- an optical transmitter adapted to transmit an optical signal;
 - a transmitting fiber in optical communication with the transmitter;
 - a dispersion and dispersion slope compensating optical fiber in optical communication with the transmission fiber, the optical fiber comprising:
 - a central core segment having a relative refractive index;
 - a depressed moat segment on the periphery of the central core segment and having a relative refractive index that is less than the relative refractive index of the central core segment;
 - an annular ring segment on the periphery of the depressed moat segment and having a relative refractive index that is less than the relative refractive index of the central core segment and greater than the relative refractive index of the depressed moat segment; and
 - a cladding layer on the periphery of the annular ring segment and having a relative refractive index that is less than the relative refractive index of the annular ring segment and greater than the relative refractive index of the depressed moat segment; and
 - an optical receiver in optical communication with the compensating fiber; and
 - wherein the relative refractive indices of the compensating fiber are selected to provide within the compensating fiber:
 - negative dispersion at a wavelength of within the range of from about 1530 nm to about 1620 nm;
 - negative dispersion slope at a wavelength of within the range of from about 1530 nm to about 1620 nm;
 - a $kappa$ value of within the range of about 40 to about 60 at a wavelength of about 1550 nm; and
 - a fiber cut-off wavelength of less than about 1550 nm.

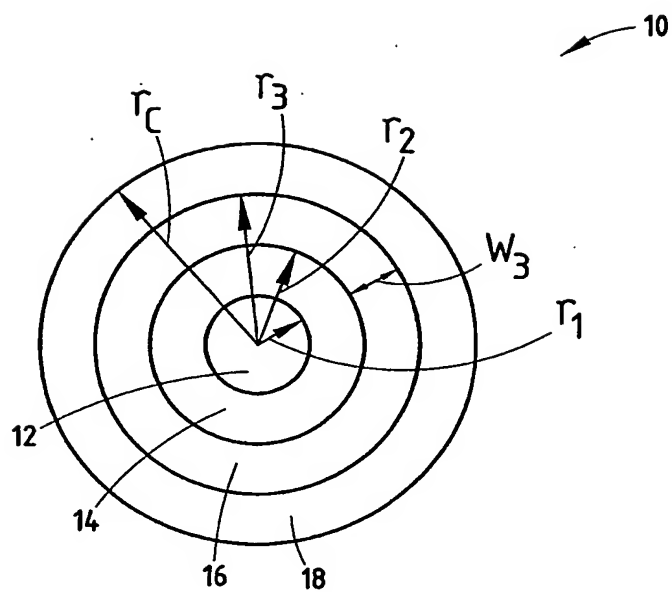


FIG. 1

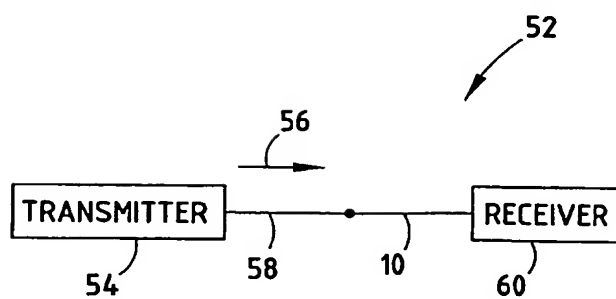
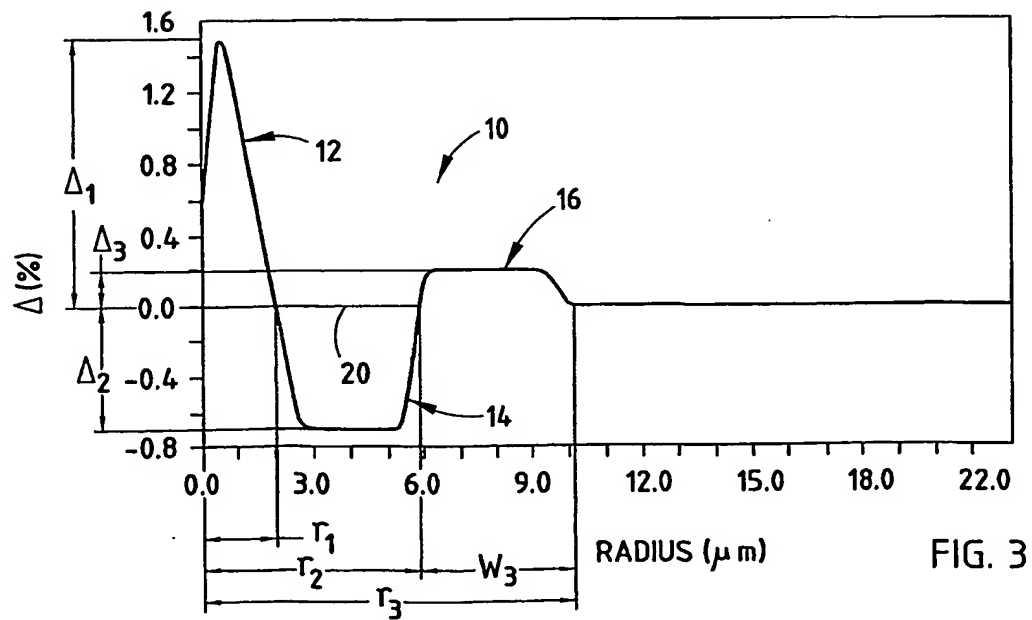
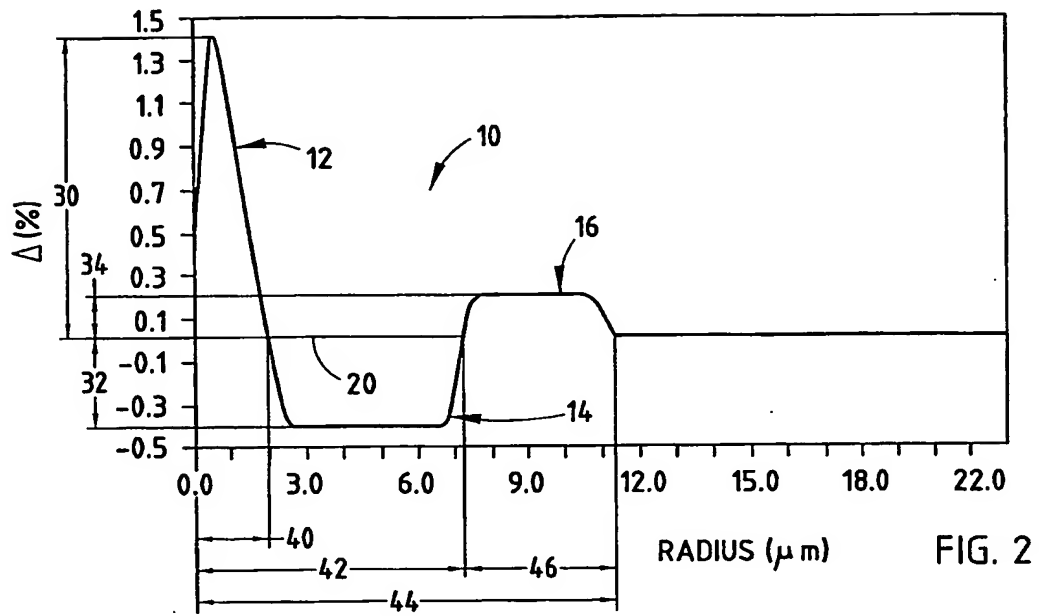
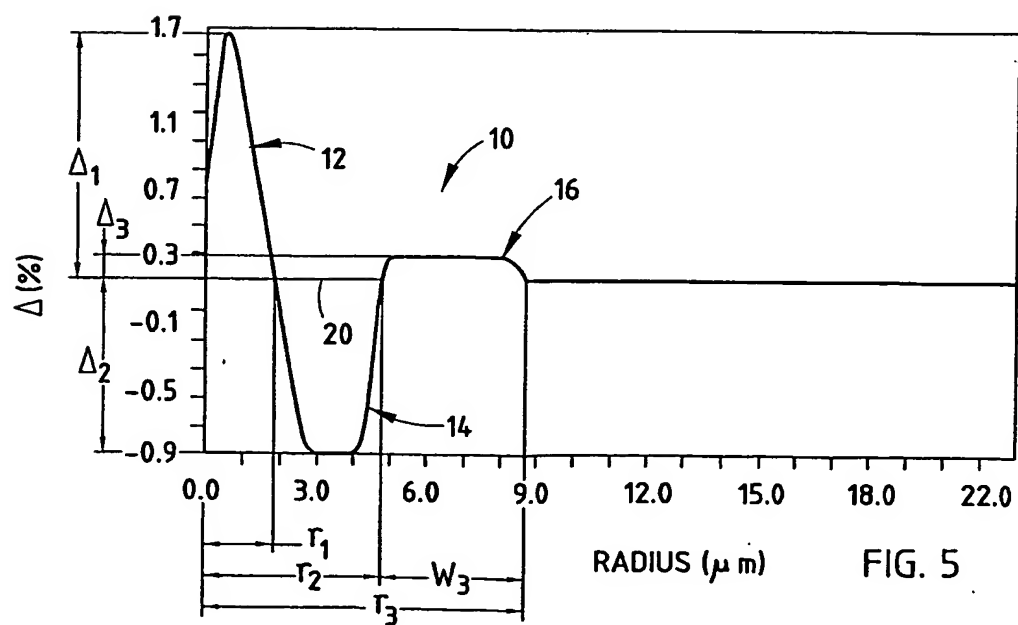
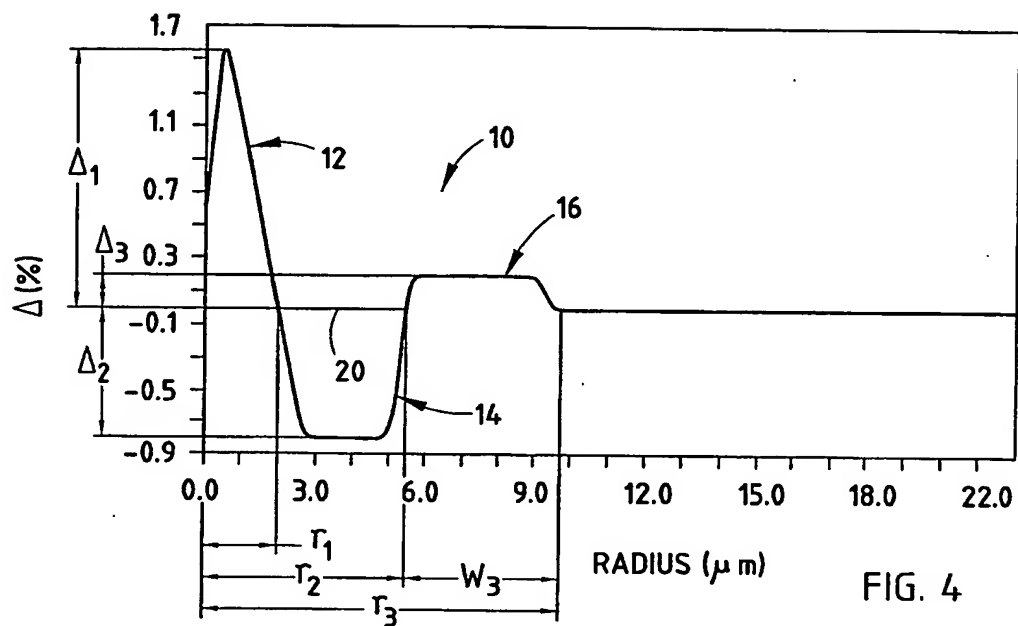


FIG. 8





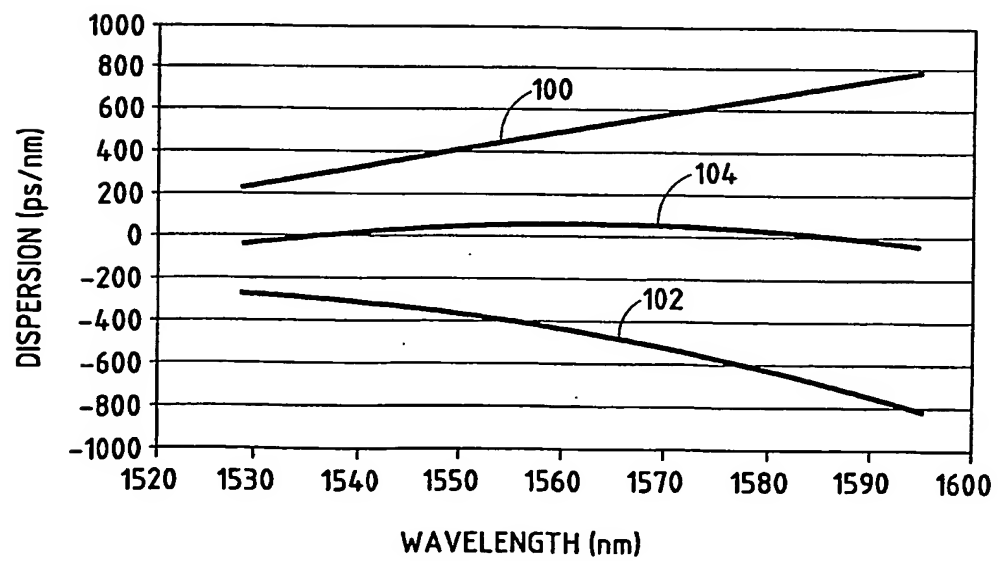
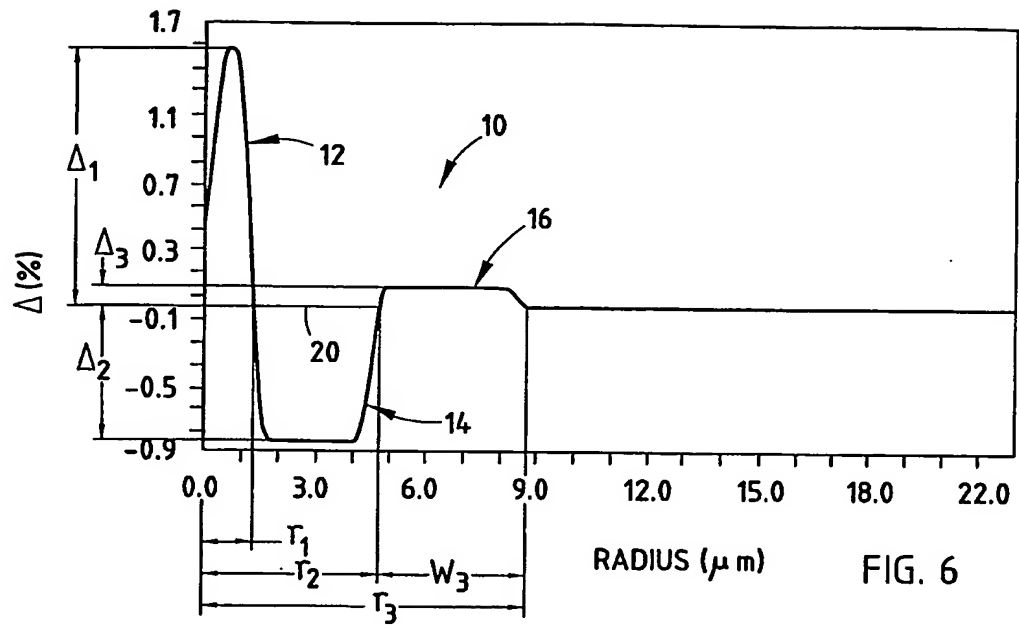


FIG. 7

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 02/35859

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G02B6/16 G02B6/22 H04B10/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G02B H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	EP 1 130 428 A (SUMITOMO ELECTRIC INDUSTRIES) 5 September 2001 (2001-09-05) column 14, line 18 -column 20, line 45	1-14
Y	WO 00 33114 A (CORNING INC) 8 June 2000 (2000-06-08) page 12, line 27 -page 13, line 7	7,8
A	WO 00 67053 A (CORNING INC) 9 November 2000 (2000-11-09) page 13, line 28 -page 15, line 20 -/--	1-14

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

2 April 2003

Date of mailing of the international search report

11/04/2003

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 02/35859

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